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Implementing the Blue Economy: Analysis of indicator interrelationships across countries and over time

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ABSTRACT

The Blue Economy aims to foster equitable and sustainable economic development by balancing ecological, governance, and economic factors. Tracking progress relies on a set of indicators, with the assumption that improvements in one area lead to progress in others. However, the empirical correlations among these indicators are often overlooked or untested, and this can contribute to inefficient or conflicting policies. This study examines the empirical statistical relationships among 21 datasets of indicators related to the Blue Economy, both across countries (cross-sectional), and within countries over time (longitudinal). We classify relationships as direct (positive correlation), inverse (negative correlation), or neutral. Results suggest that, across countries, there is statistical evidence of direct correlations in ecological, economic, and governance indicators (52% direct, 48% neutral), indicating that improvements in one area might generally support progress in others. However, when analysed over time (e.g., 2000–2019), correlations between indicators within each country become predominantly neutral, although slightly more diverse (8% direct, 86% neutral, 6% inverse). This means that common assumptions on co-benefits of development progress may not hold over time due to more nuanced and dynamic interactions within individual countries. As the first study analysing the empirical relationships of indicators commonly used in the Blue Economy, we discuss how selecting analytical approaches can yield distinct insights. By incorporating both cross-sectional and longitudinal perspectives, future research could provide a more holistic framework for implementing policies and decision-making strategies that effectively address the social, environmental, and economic dimensions of the Blue Economy.

1. Introduction

An increasing focus on implementation has highlighted the broad and varied nature of the Blue Economy (Voyer et al., 2018), which encompasses diverse perspectives on community livelihoods, business interests, ecosystem health, ecological services, assets, and technological innovation (Cisneros-Montemayor et al., 2022). Although the Blue Economy was proposed as an approach focused on equitable processes and outcomes from ocean sectors, the term poses fundamental conflicts of interest regarding the goals and pathways of development, and therefore different definitions depending on the end-users. For example, some approaches lean away from a focus on equity and advocate for growth and development, emphasizing the economic opportunities by using ocean resources, while others call for prioritizing the protection of these resources to ensure long-term sustainability (Martínez-Vázquez et al., 2021). The difference of perspectives reflects the complex and often competing definitions of the Blue Economy, which hinders the efforts to advance equity goals among economic and environmental pressures.

This broad scope of a Blue Economy involves evaluating a diverse range of enabling conditions and outcomes across social, environmental, economic and governance dimensions (Cisneros-Montemayor et al., 2019). For instance, to evaluate economic viability, metrics or indicators such as national stability and investments in marine infrastructure have been used. To estimate resource availability, metrics could include contributions from sectors like blue carbon, blue energy, and fisheries. Regarding social equity, indicators often encompass aspects such as coastal community well-being and the access to and equitable distribution of marine resources among different groups. To assess environmental sustainability, indicators may focus on biodiversity health

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(including extinction rates), marine habitat preservation, water quality, and resilience to climate change impacts (Cisneros-Montemayor et al., 2021; Halpern et al., 2012; Rockström and Sachs, 2013). Additionally, social indicators focusing on well-being, inequality, governance, policy effectiveness, and coherence play a crucial role in measuring regulatory frameworks, the enforcement of marine conservation laws, and stakeholder participation in decision-making processes (Hicks et al., 2016; Voyer et al., 2021). Together, these indicators might help to highlight the required/desired conditions for an equitable and sustainable Blue Economy (N. J. Bennett et al., 2019; Cisneros-Montemayor, 2019; Cisneros-Montemayor et al., 2021). Identifying and understanding the relationships between diverse indicators is essential for enhancing policy development and decision-making in Blue Economy practices. These interrelationships, which often span across economic, environmental, and social dimensions, influence the effectiveness and sustainability of governance approaches and require careful analysis to identify potential synergies and trade-offs. The diverse analytical approaches used in studies of the Blue Economy provide a comprehensive framework for evaluating its sustainability from different perspectives and may help guide policymakers and stakeholders toward informed decision-making. For instance, understanding correlations among variables—especially within the various dimensions of the Blue Economy—can help identify which indicators carry more significant information and which may be redundant (DeSarbo et al., 2016). This understanding can aid in prioritizing data collection, ultimately enhancing the effectiveness of policy formulation, as demonstrated in a case study of Panama, where aligning existing ocean policies with Blue Economy objectives was shown to improve policy coherence (de Ycaza et al., 2024). Practically, this search can help identify a minimum set of highly informative indicators that can track progress across the various indicators that highlight multiple aspects within broad dimensions (e.g. within environmental, social, economic, or governance), to aid in tracking complex criteria or create composite indicators that are not inflated with redundant information (Flavio et al., 2018; Gan et al., 2017; Schmidt-Traub et al., 2017). For example, income is often positively correlated with education indicators (Gan et al., 2017), partly because there is often a causal dependency between the two, and tracking both can put effort and resources into redundant information, which may be important for organisations trying to determine what indicators to monitor.

Recent studies on the Blue Economy have employed a variety of analytical approaches, each offering valuable insights into different aspects of its development. For example, meta-analyses and systematic reviews (e.g., Crona et al., 2021; Smith-Godfrey, 2022) provide comprehensive overviews of interactions between ocean sectors and the performance of key indicators, which help identify sectoral synergies and trade-offs. On the other hand, quantitative methods (e.g., Cisneros-Montemayor et al., 2021; Ni et al., 2024; Martínez-Vázquez et al., 2023) are increasingly used to assess the capacity of nations to achieve a sustainable Blue Economy by examining causal relationships and the effects of changes in one sector on others, such as coastal tourism, maritime transport, and ocean energy. Comparative assessments (e.g., Wuwung et al., 2022), offer a global perspective by developing databases for national-level governance analysis, while mixed methods (e.g., Benzaken et al., 2022) explore the governance challenges and implementation barriers to the Blue Economy concept. These studies, using a range of approaches, highlight the complexity and multidimensionality of the Blue Economy and suggest that a multi-method approach can be particularly valuable for capturing the interplay between the social, economic, and environmental dimensions across different regions and sectors.

Therefore, the choice of analytical method can, at the same time, significantly influence the formulation of policies and decision-making strategies. The reason is because, cross-sectional approaches, whether qualitative or quantitative, provide snapshots of the conditions at a single point in time, offering valuable insights for immediate policy adjustments. In contrast, longitudinal analyses track changes in their conditions over time and usually at more local scales, providing a view of trends and developments that can inform long-term and more dynamic strategic planning (Kim, 2021; Wang and Cheng, 2020). The longitudinal approach offers critical insights into the temporal dimensions of Blue Economy indicators, highlighting how relationships evolve over time and in response to broader global shifts.

This study compares cross-sectional and longitudinal analyses to highlight how different analytical methods can provide complementary perspectives. Cross-sectional studies offer insights into current relationships between indicators, while longitudinal analyses provide a more dynamic view that reflects changes and trends over time. Both approaches enhance the understanding of Blue Economy indicators and are essential for designing policies that are both adaptive and forward-thinking. This paper shows how combining cross-sectional and longitudinal approaches offers deeper insights into the complex, multidimensional nature of the Blue Economy, particularly within its socioeconomic and environmental dimensions. Therefore, this study highlights the importance of recognising methodological differences to ensure more accurate interpretations of results, ultimately contributing to the development of robust, adaptive policies for a sustainable Blue Economy.

2. Materials and methods

2.1. Data acquisition

There are hundreds of possible indicators related to the various aspects of development under a Blue Economy. For this study, we focused on a subset of 21 indicators (see Table 1) selected from Cisneros-Montemayor et al. (2021) which provides a comprehensive set of global indicators explicitly designed to integrate key aspects of social equity, environmental sustainability, and economic viability. These indicators have been widely recognised for their relevance in assessing the multifaceted dimensions of the Blue Economy, and their use allows for a structured evaluation of the capacity of countries to establish an equitable, sustainable, and viable Blue Economy. By focusing on these specific indicators, we aim to provide a nuanced understanding of the Blue Economy, grounded in both the environmental and socio-economic

Table 1
Blue Economy indicators considered for the analyses (n = 21). The dimensions and criteria related to each indicator are also included. The list was based on previous research of Cisneros-Montemayor et al. (2021).

Dimension	Criteria	Indicator
Social Equity	Human Rights	Human rights and rule of law
	Gender Equality	Gender inequality index
	Group Equity	Group grievance
		Factionalized elites
	Economic Equity	Economic inequality
		Human flight and brain drain
	Corruption	Control of corruption
Economic Viability	National Stability	State legitimacy
		Government effectiveness
	Investment Risk	State of the economy
		Investor protection index
		Regulatory quality
		Business environment
	Infrastructure	Public services
		Port infrastructure
		Shipping connectivity
		Air transport
		Secure internet servers
Environmental Sustainability	Habitat	Biodiversity - Habitat
	Biodiversity	Biodiversity - Species
	Water Quality	Clean waters

contexts of ocean and coastal development. Subsets of these indicators are widely used in related scenario analyses (e.g., N. J. Bennett et al., 2019; Hodgson et al., 2019; Ocean Health Index, 2022). All of the indicators employed in this study are available individually or within composite indexes from official national or intergovernmental sources, such as the World Governance Indicators (Kaufmann and Kraay, 2023), World Tourism Organization (UNWTO, 2022), Fragile States Index (2022), United Nations Development Programme and World Bank statistical datasets, and Ocean Health Index (Halpern et al., 2012; Ocean Health Index, 2022).

Given the complex and multidimensional nature of the Blue Economy, we ensured that the selected indicators were representative of each key dimension: social equity, economic viability, and environmental sustainability. This approach was critical for understanding the relationships and potential correlations between these dimensions.

2.2. Cross-sectional and longitudinal analyses

Similar to correlations within Sustainable Development Goals (SDGs), the relationships between Blue Economy indicators can evolve and be context-dependent due to socio-economic conditions, governance, or geographical location (Singh et al., 2018). This means that a positive relationship in one context may appear negative in another due to varying influencing factors. Therefore, to gain a comprehensive understanding of how Blue Economy indicators relate to each other, we conducted both cross-sectional and longitudinal correlation analyses using the nonparametric Spearman's rank correlation analysis. This approach provides an initial systematic overview and comparison of correlations among Blue Economy indicators from both longitudinal and cross-sectional perspectives (Table 2).

To ensure uniformity among all indicators, we reversed the values for those indicators where lower values represent better performance. For example, in the original data source a lower value on the "state legitimacy" indicator suggests a better performance, while a lower value on the "government effectiveness" indicator may indicate poorer performance, so this would be rescaled so that lower numbers denote “worse” and higher numbers “better”. This process of value normalization ensured that all indicators were treated consistently across the analysis, minimizing the potential for misleading results due to differing scales or interpretations of performance across variables.

In the cross-sectional analysis, we assessed the correlations among indicator pairs at a specific point in time across countries (e.g., the correlation between two indicators across countries in 2019). To evaluate the consistency of these results, we also aggregated the data by country across the long-term period (e.g., 2000–2019). For the longitudinal analysis, we examined how correlations between indicators changed over time by analysing the pairwise relationships of the time series of each indicator within individual countries (e.g., the pairwise correlation between the period 2000–2019 for each country). At this stage, we applied a detrending step using a linear regression model. Detrending accounts for short-term variability in the data that could mislead the correlation outcomes, by focusing on the underlying trends in the data. This process involved fitting a linear model to each indicator's time series, allowing us to isolate the residuals, which represent the detrended values (see Fig. S1). We then used these detrended values to classify the correlations in the longitudinal analysis. Incorporating detrending into the analysis was crucial for isolating the long-term structural changes in the indicators from shorter-term fluctuations that may be influenced by external factors, such as political or economic crises.

While more recent data are available for most of the indicators, we decided to only use data prior to the SARS-CoV-2 pandemic (the year 2019) to avoid any potential misinterpretation of outcomes. Due to delays in data collection and reporting it, in most cases, this excludes

Table 2
Comparative synthesis of advantages and disadvantages of Cross-Sectional and Longitudinal correlation analyses in the context of the Blue Economy.

Cross-Sectional Analysis	Longitudinal Analysis
Advantages	
Provides a snapshot of a single point in time; useful for understanding the current conditions of the correlations.	Captures how relationships between indicators change over time, providing insights into complex dynamics.
Easier and quicker to perform with suitable and available data.	Helps in identifying trends and shifts in indicators' relationships.
Useful for performing multiple comparisons across different countries or regions.	Allows multiple comparisons of indicators within different countries or regions.
Disadvantages	
Does not account for changes over time, potentially missing dynamic interactions.	Requires more complex data management and timeframes, which can be resource-intensive.
May not capture the impact of temporal factors, leading to potential misinterpretation of causal relationships.	It can be difficult to acquire a consistent database over time. Missing data or inconsistent data collection may also represent a challenge.
Limited in assessing the direction and strength of changes in indicator relationships.	More challenging to interpret due to potential confounding factors and temporal variability.
Policy and decision-making implications	
Can facilitate the prompt development of policies and ease decision-making based on current conditions. However, it may result in less responsive decision- and policy-making to dynamic changes.	It supports long-term planning by revealing trends and shifts over time, enabling more adaptive policy-making. However, it may require more complex data management and could face challenges with data consistency.

two to three years of data for each country, and indicators generally go back to 2021. Using pre-pandemic data will help us understand the baseline conditions before the significant disruptions caused by the COVID-19 pandemic, which affected sectors such as fisheries, aquaculture, renewable ocean energy, seaports, shipping, seabed mining, marine biotechnology, and marine tourism (Sharma and Sharma, 2020).

2.3. Classification of interactions

The coefficient of the Spearman test, (ρ; Rho), ranges between $+1$ and -1, indicating direct or inverse monotonic associations, respectively. Using this coefficient, the correlation results were classified into three categories: “Direct” for $\rho > 0.6$ with a p-value <0.05, “Inverse” for $\rho < -0.6$ with a p-value <0.05, and “Neutral” for $-0.6 \leq \rho \leq 0.6$ with a p-value >0.05. The categorisation approach is similar to those used to assess synergies and trade-offs in Sustainable Development Goals (De Miguel Ramos and Laurenti, 2020; Kroll et al., 2019; Pradhan et al., 2017). Similarly to Pradhan et al. (2017) work, we limited our analysis to data pairs with more than five data points to minimize the risk of false direct or inversed relationships resulting from a small dataset.

In addition, we considered the context in which the correlations were observed, taking into account the temporal and spatial dynamics that might influence the strength and direction of relationships between indicators. This approach adds a layer of complexity to the categorisation but helps ensure more robust conclusions.

We conducted the analyses only for paired indicators belonging to the same dimension. For example, we compared "gender inequality" and "human rights," both from the "social equity" dimension, but not "gender inequality" versus "shipping connectivity," which are from different dimensions and may involve complex relationships. By focusing on indicators within the same dimension, we ensure that our analyses are more meaningful and directly relevant, enhancing the validity of our findings. Additionally, while correlations may exist between indicators across different dimensions, these relationships could be indirect and fall outside the scope of this study. Furthermore, the focus of this study does not permit an exploration of the causal effects of each paired relationship. This focus on intra-dimensional indicator pairs also helps to mitigate potential biases that might arise from exploring relationships between variables that span multiple dimensions, which could complicate the interpretation of their interactions.

Likewise, we computed the direction and strength of trends for each indicator by country to assess how each indicator’s performance changed over time. These trends were derived from linear regression analyses applied to detrended time series data, where the trend represents the slope of the fitted line (Fig. 1a). Analysing the slope for each indicator, whether positive or negative, could help in inferring the nature of the correlation between paired indicators. A direct correlation was distinguished if both indicators exhibited either positive or negative trends simultaneously (Fig. 1b), while an inverse correlation occurs if one indicator showed a positive trend and the other a negative trend (Fig. 1c). A neutral correlation indicates an absence of a clear relationship (Fig. 1d). This approach offers insights into how evolving trends in individual indicators may influence their relationships over time and may help explain any differences between cross-sectional and longitudinal analyses.

By combining these methods, the study not only captures the static relationships between indicators at a given point in time but also reveals how their interactions evolve in the long term, enabling more

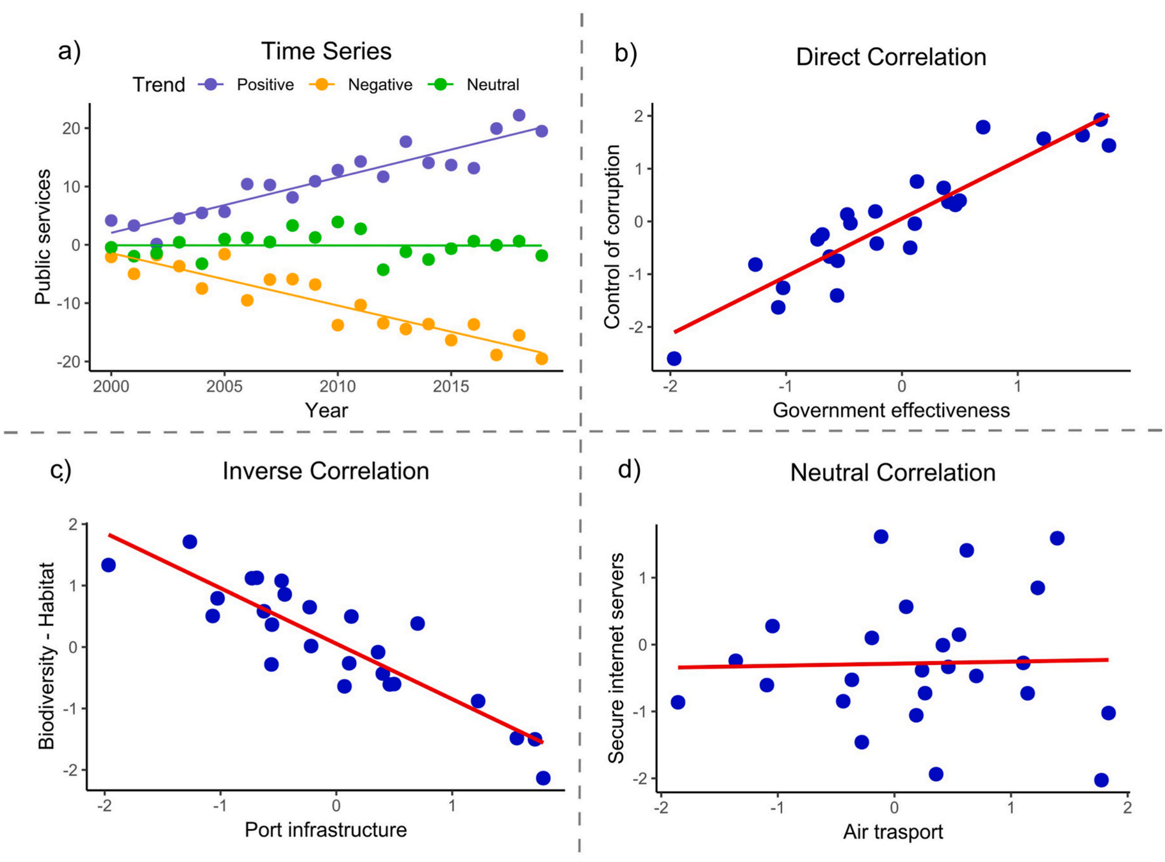

Fig. 1. Theoretical plots illustrating different types of correlations and trend lines. We used synthetic values just as a reference. Panel (a) presents theoretical trends for one single variable (e.g. "Public Services"), demonstrating positive, negative, and neutral trends over time. Panel (b) shows a direct correlation between "Government Effectiveness" and "Control of Corruption". Panel (c) depicts an inverse correlation between "Port Infrastructure" and "Biodiversity - Habitat". Panel (d) illustrates a neutral correlation, where there is no apparent relationship between "Air Transport" and "Secure Internet Servers".

comprehensive policy recommendations.

All the analyses were performed using R project version 4.2.1 (R: The R Project for Statistical Computing).

3. Results

In total, 158 correlations were performed across the 21 Blue Economy indicators, with 79 conducted in the cross-sectional analysis and 79 in the longitudinal analysis. This included 55 correlations between paired indicators within the Economic Viability dimension, 21 pairwise comparisons within the Social Equity dimension, and 3 correlations within the Environmental Sustainability dimension (Fig. 2a–f).

3.1. Cross-sectional analysis

In the cross-sectional analysis of the 79 relationships, 42 were classified as direct (positive) and 37 as neutral, with none categorized as inverse. This distribution indicates that approximately 53% of the relationships were direct, while 47% were neutral. Within the dimensions, the Social Equity dimension had the highest proportion of direct relationships, with 90% (19 out of 21), followed by the Economic Viability dimension at 54% (23 out of 42). Notably, there were no direct relationships observed in the Environmental Sustainability dimension. Conversely, all neutral relationships were found exclusively within the Environmental Sustainability dimension, with the Economic Viability dimension accounting for 86% (32 out of 37) of neutral relationships, and only 10% (2 out of 19) in the Social Equity dimension (Fig. 2a–c).

When examining the distribution of correlation types among pairwise indicators, it was observed that correlations involving either the "Air Transport" or "Secure Internet Servers" indicators in the "Economic Viability" dimension consistently resulted in "neutral" relationships. These neutral relationships might reflect the fact that, although both

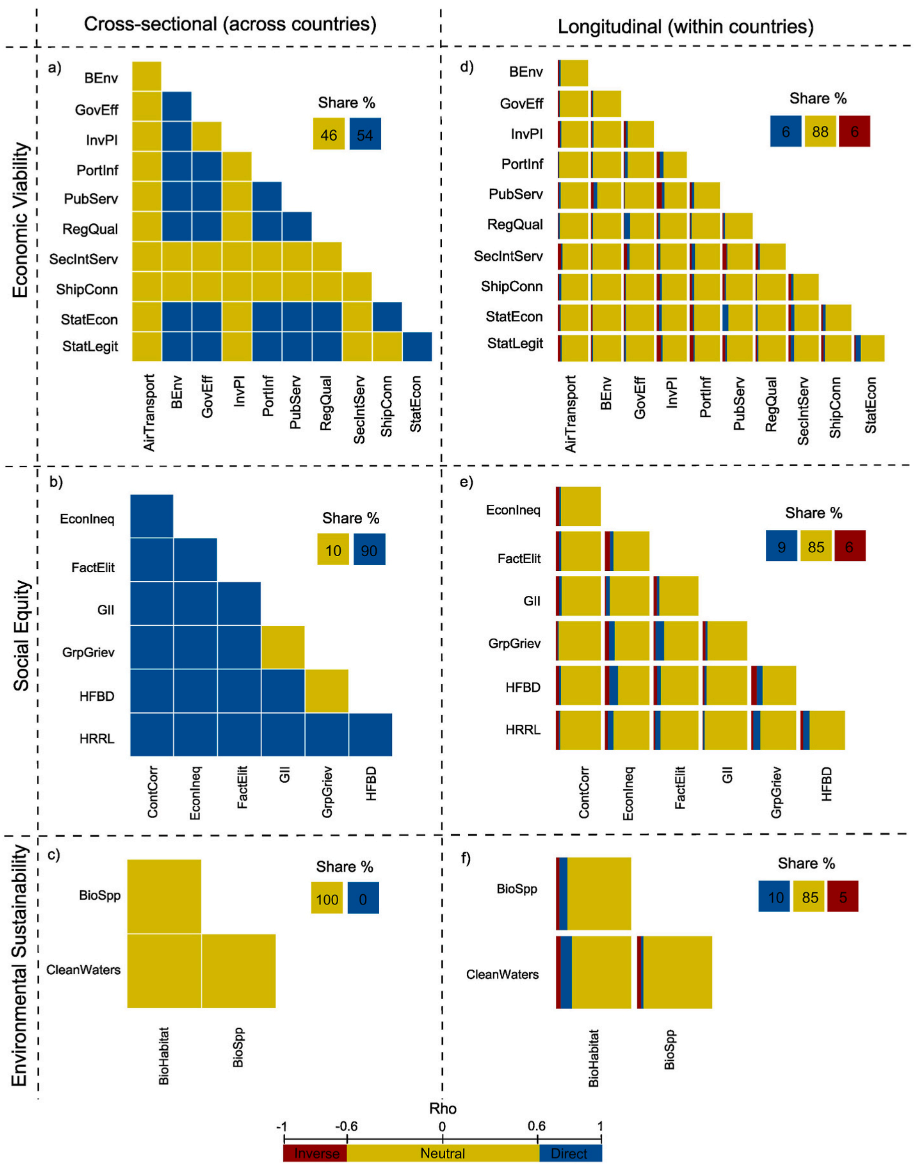

Fig. 2. Relationships between Blue Economy indicators (n = 21). The colour of the charts represents the shares of direct (blue), neutral (yellow), and reverse (red) relationships between the indicator's pairs across or within countries (Cross-sectional and longitudinal, respectively) by dimensions (Economic Viability, Social Equity, Environmental Sustainability). Each indicator is represented by its abbreviation; Air transport (AirTransport), Biodiversity - Habitat (BioHab), Biodiversity - Species (BioSpp), Business environment (BEnv), Clean waters (ClearWaters), Control of corruption (ContCorr), Economic inequality (EconIneq), Factionalized elites (FactElit), Gender inequality index (GII), Government effectiveness (GovEffec), Group grievance (GrpGriev), Human flight and brain drain (HFBD), Human rights and rule of law (HRRL), Investor protection index (InvPI), Port infrastructure (PortInf), Public services (PubServ), Regulatory quality (RegQual), Secure internet servers (SecIntServ), Shipping connectivity (ShipConn), State legitimacy (StatLegit), State of the economy (StatEcon).

indicators are part of the broader infrastructure and connectivity landscape, their impact on Blue Economy sectors may be indirect or dependent on other factors. This implies that these indicators did not show any trend towards positive or negative relationships with other indicators. Similarly, indicators such as "Control of Corruption," "Economic Inequality," "Factionalized Elites," and "Human Rights and Rule of Law" within the "Social Equity" dimension consistently exhibited a "direct" relationship when paired with other indicators (Fig. 2a–c).

3.2. Longitudinal analysis

The longitudinal analysis revealed the presence of all three types of interactions—direct, neutral, and inverse—among the 79 pairwise correlations. In the dimensions of Economic Viability, Social Equity, and Environmental Sustainability, neutral interactions were the most common, representing more than 80% of the correlations, in either dimension. Direct correlations, ranged between 6% and 10%, while inverse relationships were the least common, accounting for between 5% and 6% of the correlations across the different dimensions (Fig. 2d–f).

When examining the proportion of correlations by indicator within each dimension, it was found that no pairwise correlation consistently resulted in only direct, inverse, or neutral relationships. This variation emphasises the dynamic nature of these interactions over time, suggesting that the effects of specific indicators may evolve as countries or regions adapt to changing conditions. In the Economic Viability dimension, the most common direct relationship was observed between "Regulatory Quality" and "Government Efficiency" (19%), whereas the most frequent inverse relationship was between "Public Services" and "Investor Protection Index" (17%) (Fig. 2d). Within the Social Equity dimension, the most prevalent direct correlation was between "Economic Inequality" and the "Human Flight and Brain Drain" (19%), with the most significant inverse correlation observed between the "Human Flight and Brain Drain" and "Group Grievance" (12%) (Fig. 2e). In the Environmental Sustainability dimension, the most common direct relationship was between "Biodiversity – Habitat" and "Clean Waters" (14%), while the most notable inverse correlation was between "Clean Waters" and "Biodiversity – Habitat" (6%) (Fig. 2f).

4. Discussion

The Blue Economy involves a wide range of socioeconomic activities centred on the sustainable use of marine resources. Implementing this concept is complex, as different sectors and goals are intrinsically interrelated experiencing both positive and negative interactions. Moreover, the choice of analytical approach to assess them—whether cross-sectional or longitudinal—can provide different outcomes and interpretations. Our research compares these approaches by analysing the relationships among indicators across social equity, economic viability, and environmental sustainability dimensions, both across and within countries. In the following sections, we discuss why relationships between indicators may vary based on the analytical approach performed by selecting pairwise relationships as an example to illustrate how the nature of these relationships can shift over time and across different contexts.

4.1. Correlations between indicators: cross-sectional and longitudinal perspectives

Our analysis highlights the importance of understanding how different analytical approaches can influence the interpretation of relationships between indicators in the Blue Economy. The results presented above demonstrate that while some indicators may appear to have strong positive or neutral relationships when viewed in a cross-sectional approach, these relationships can change when examined over time using a longitudinal perspective. That is, the predominantly direct or neutral relationship found in a cross-sectional analysis stems from the fact that each indicator's value for a given country represented a single observation at one point in time. Conversely, a longitudinal analysis, which involved tracking the values of indicators over multiple years for each country, uncovered inverse correlations (up to 6%) that may not be evident from the static snapshot of the cross-sectional analysis. This suggests that long-term trends and shifts in governance, environmental or economic structures might reveal challenges that are not apparent in cross-sectional snapshots. Therefore, the shift from predominantly direct or neutral relationships in cross-sectional to a broader range of relationships in the longitudinal approach, even if small, can reveal underlying trends, shifts, or emerging challenges that are critical for sustainable ocean governance. Longitudinal analyses can uncover delayed effects or hidden patterns, allowing for more robust policy interventions to mitigate potential risks. On the other hand, the prevalence of neutral relationships in the longitudinal analysis (up to 88%) may also suggest that the indicators are measuring different aspects within the same dimension, with little shared information between them. The stability of interactions over time could simply reflect the distinct nature of the indicators, preventing significant shifts toward positive or negative correlations. While it's still interesting to explore why some countries experienced positive or negative trends, this level of analysis is not the focus of the current paper.

For decision-makers, policy-makers, and practitioners, relying solely on cross-sectional data might provide a simplified overview of the scenario but potentially a misleading picture of the dynamics at play over time and in more specific contexts, underscoring the need for careful consideration of the temporal dimension in policy decisions. One actionable step is to integrate both cross-sectional and longitudinal approaches into policy analysis. Specifically, policymakers could use cross-sectional studies to identify immediate sectoral gaps and governance challenges, while also engaging in longitudinal analysis to anticipate future dynamics and adjust policies accordingly. A mixed-method approach (e.g., integrating cross-sectional snapshots with longitudinal trend analysis) can offer a more comprehensive understanding of the Blue Economy's complexity and improve policy resilience. Furthermore, the lack of consistency in the correlative analysis, coupled with the absence of consistent longitudinal relationships within the Blue Economy dimensions, highlights that monitoring and accounting frameworks based on a limited set of indicators are unlikely to capture the full range of trends within these dimensions. Though tracking some restricted set of indicators might be attractive based on resource constraints in information gathering, our results suggest that this approach could lead to incomplete accounts of the trends within the Blue Economy.

By examining the relationships between indicators from the economic viability, social equity, and environmental sustainability dimensions, a cross-sectional analysis could help in identifying potential strengths and weaknesses across different countries or regions. Having a snapshot of these indicators provides a baseline for evaluating existing gaps and developing strategies and policies that enable scenario analyses to explore the potential impacts of proposed changes in the short term. For example, cross-sectional studies can serve as a starting point to identify critical gaps in infrastructure, governance, or environmental protection that can later be addressed in longitudinal analyses to assess long-term progress. A practical recommendation here is that policymakers should use cross-sectional studies to identify key policy intervention points, followed by longitudinal tracking to assess the long-term effects of these interventions. This cyclical process would ensure continuous policy improvement. For instance, a recent cross-sectional study using a selected set of available indicators emphasised that based on the current conditions by the time of the analysis, achieving an equitable and sustainable Blue Economy requires more than just resource availability; further strategies must also address social, economic, and governance conditions specific to each country (Cisneros-Montemayor et al., 2021). Similarly, another recent cross-sectional analysis performed by Crona et al. (2021), identified interactions between economically important ocean sectors by reviewing 3187 articles. The study mapped 93 unique direct and 61 indirect interactions, often mediated by the ocean ecosystem. This study revealed that while some sectors, like renewable energy and tourism, coexist synergistically, many interactions are antagonistic, leading to negative effects on other sectors via marine ecosystem degradation. In this case, the study stressed how cross-sectional studies can provide a comprehensive snapshot of sectoral interactions and their impacts, highlighting the need for informed governance strategies to manage trade-offs and opportunities in the Blue Economy. This is a good example of how a cross-sectional study can highlight immediate sectoral tensions, but a longitudinal perspective would be crucial for understanding how these interactions evolve and how mitigation strategies may need to change over time.

On the other hand, performing a longitudinal analysis is an essential step for scenario analyses of the Blue Economy and similar development strategies, as it provides a dynamic view of how relationships between indicators may change through time. Longitudinal data is crucial for understanding causal relationships, offering more robust insights than cross-sectional correlations. For instance, consider the relationship between "Clean Waters", "Biodiversity – Habitat" and "Biodiversity – Species". While the cross-sectional analysis may show a "neutral" association among these indicators, ecological principles suggest that improved water quality enhances habitat conditions, supporting diverse and resilient species populations (Duarte et al., 2020). This lack of direct relationships in Environmental Sustainability indicators may reflect the complexity of environmental dynamics, which may not align as clearly with economic or social factors. Further investigation could explore whether environmental indicators exhibit stronger connections when considered in isolation or across a different set of countries or regions. For instance, results from longitudinal correlation analysis might reveal instances where improvements in "Clean Waters" are linked to a decrease in "Biodiversity – habitat" or "Biodiversity – Species", indicating a delayed direct effect or suggesting that other factors, such as resource allocation and funding priorities undermine initial progress.

Specifically, the inverse correlation between "Clean Waters" and "Biodiversity – Habitat" may highlight potential tensions between economic activities like coastal development or tourism and environmental preservation efforts. Further analysis of these opposing dynamics may help identify where policies could be tailored to reduce such trade-offs. For example, inverse relationships may arise in situations when inadequate efforts to reduce contamination by chemicals, excessive nutrients (eutrophication), human pathogens, and other types of waste (Butler et al., 2013), can hinder expected outcomes in aquatic habitat functions and ecosystem services, thereby affecting the species biodiversity. Moreover, these complexities are, indeed, often exacerbated by overlapping jurisdictions and institutional constraints (Ruttenberg and Granek, 2011). Such challenges reinforce the idea that achieving environmental sustainability requires coordinated policy actions across different governance levels. For instance, in a review of policy instruments implemented in Great Barrier Reef (GBR) catchments, continuous efforts over 20 years to reduce the impacts of agriculture on water quality in downstream marine ecosystems seem to have not yielded sufficient progress. The authors note that the lack of robust evidence to assess the effectiveness of instruments such as agricultural extension, financial incentives, and direct regulation of farming practices, may be related to the weak program evaluation, and heterogeneity of agricultural entities (Eberhard et al., 2021). The latter highlights the challenge of resource allocation and the need for improved understanding and evaluation of policy instruments to achieve balanced environmental goals. The case of the Great Barrier Reef highlights a critical lesson for management; the importance of continuous monitoring, program evaluation, and adaptive refinement of policy instruments. In situations where policy interventions do not produce the expected results, such as with the agricultural efforts in the GBR catchments, it is essential to implement mechanisms that allow for ongoing evaluation and real-time adjustments to strategies. This underscores the need for adaptive management frameworks that incorporate feedback loops, enabling interventions to be periodically assessed for effectiveness and adjusted based on observed outcomes.

Taking a forward-looking perspective is crucial for enhancing policies, creating adaptable plans, and anticipating future possibilities and challenges that arise from long-term trends. For policy-makers, it is essential to incorporate long-term, trend-based analyses and adaptive management strategies such as scenario-based planning into their decision-making processes. This approach enables decision-makers to consider multiple potential future scenarios and develop policies that are flexible and resilient to a variety of changing circumstances. Additionally, longitudinal analysis can help identify patterns and trends within a nation that would not be seen in cross-sectional snapshots. Policymakers should not only rely on short-term goals but ensure their plans are adaptable and informed by long-term projections to sustain the Blue Economy's social, economic, and environmental dimensions over time.

Finally, the trends in individual indicators by country were analysed in detail and can be found in Supplementary Material (Trends by indicator, Fig. S2). These trends revealed both positive and negative patterns across different countries and regions, which highlight the complexity of Blue Economy outcomes. Just as importantly, this highlights the importance of considering whether causal relationships—even if theoretically well-justified—can be observed in the types of data and scales collected for national and regional development and sustainability indicators.

4.2. *Limitations of analytical methods*

Both cross-sectional and longitudinal analyses offer valuable insights but come with notable limitations. Since cross-sectional analyses may obscure temporal changes and variations across different contexts, adopting this approach could potentially lead to get generalized conclusion. For example, in a recent study across 166 countries, Wen et al. (2021) highlight that government efficiency significantly enhances innovation output. However, this conclusion may not account for how the impact of government efficiency on innovation might evolve or vary between different stages of economic development. The study's snapshot view may miss important variations, such as how incremental improvements in bureaucracy quality and regulatory processes contribute to long-term innovation trends. This illustrates the limitation of cross-sectional approaches in capturing the full temporal dimension of complex governance factors. Thus, while cross-sectional findings indicate a strong relationship between efficient government operations and higher innovation output, longitudinal studies are necessary to understand how these dynamics play out over time and across diverse contexts, providing a more comprehensive and context-sensitive analysis.

In contrast, while the dynamic view offered by longitudinal analysis can capture changes over time in relationships between indicators, it often faces challenges such as the availability and quality of time series data (Grainger, 2008), inconsistencies in data standardisation across countries (Helderop et al., 2019), and the complexity of disentangling multiple interacting factors (E. M. Bennett and Reyers, 2024). For instance, some studies have employed mixed methods to gain more nuanced perspectives, such as combining semi-structured interviews with country-specific data (Benzaken et al., 2022; Bhattacharya and Dash, 2020; Martínez-Vázquez et al., 2023). However, these approaches have generally been applied to specific states or regions rather than on a global scale, where comprehensive data availability and quality pose additional challenges.

4.3. *Implications for triple-bottom-line (TBL) development approaches*

To enhance the robustness of future research and reduce potential biases that could impact policy and decision-making, it is crucial to integrate lessons from existing studies and different perspectives. This includes improving data standardisation practices, applying advanced statistical methods to address data gaps, and exploring the correlations and relationships between sectors and indicators. In terms of how cross-sectional and longitudinal approaches can impact decision-making and policies, examining conclusions and suggestions from various research studies can be insightful, whether we are looking to understand current conditions or trends.

In the previously mentioned research of Cisneros-Montemayor et al. (2021) and N. J. Bennett et al. (2019) the authors suggest that policy-makers should engage proactively in evidence-based, collaborative planning. This approach ensures that sectors are selected thoughtfully and that the Blue Economy achieves its goals in a manner that is socially equitable, environmentally sustainable, and economically viable. Taking as an example the social equity dimension, our analysis showed that cross-sectional analysis revealed mostly direct relationships among the indicators, while the longitudinal analysis shifted many of these to neutral relationships. In some cases, these relationships even flipped to negative (Fig. 2b and e), which could reflect emerging challenges or differences in governance for those states. These instances where relationships shift could provide valuable case studies for policymakers, highlighting the potential for evolving dynamics and the need for adaptive responses. Given that these shifts may be context-specific, tailored strategies that account for the unique conditions of each state or region could be critical. Therefore, while neutral relationships were most common, a nuanced understanding of these shifts is critical to inform more effective and responsive policy decisions. Similarly, Crona et al. (2021) argue that effective decision-making and policy formulation can be enhanced by implementing a set of guiding principles. These principles are designed to manage interactions between sectors and promote sustainable and equitable development across the Blue Economy. Furthermore, integrating stakeholder engagement, particularly from marginalised or vulnerable communities, is crucial to ensure that policies reflect the needs and aspirations of all those affected by ocean governance. The insights of these cross-sectional studies are particularly relevant for understanding the broader implications of the triple-bottom-line (TBL) approach. Effective decision-making and policy formulation must consider a comprehensive range of factors and engage in integrated planning to address the complex interplay between these ocean sectors.

On the other hand, longitudinal analyses can offer valuable insights into sustainable ocean resource management and its implications for the TBL. For instance, a study on Seychelles' fisheries, spanning from 1950 to 2017, highlights the role of sovereign blue bonds and long-term baseline data in integrating sustainable practices into resource management (Christ et al., 2020). By examining long-term trends, such analyses help policymakers create realistic projections for future resource use and economic growth. This foresight enables the development of sustainable pathways that address both current and future resource needs, thereby aligning social, economic and environmental goals.

Additionally, longitudinal analyses can help uncover emerging risks and opportunities that may not be apparent when short-term data is used, allowing policymakers to anticipate and mitigate potential challenges, especially in those states where the trend shifts. For instance, the ability to forecast long-term trends in resource availability and ecosystem health is particularly important for designing adaptive management strategies that are flexible, resilient, and capable of responding to evolving environmental, economic, and social conditions. In the context of the Blue Economy, adaptive management could involve monitoring ocean health indicators over time and adjusting conservation or resource extraction policies based on observed trends. If a certain fishery is showing signs of depletion, for instance, management plans can be adjusted accordingly (e.g., implementing stricter quotas, promoting alternative livelihoods for communities, or enhancing marine protection areas) to prevent further decline.

5. Conclusions

The choice of analytical approach significantly influences the results and insights drawn from data, particularly when assessing complex, multifaceted issues like the Blue Economy. This study demonstrates the benefits of employing a mixed-methods approach that combines both cross-sectional and longitudinal perspectives, offering a more comprehensive understanding of current conditions and future trajectories. While cross-sectional analysis provides a valuable snapshot of relationships at a single point in time, longitudinal analysis reveals how these relationships evolve, allowing for the identification of trends and shifts that are critical for sustainable policy formulation. By adopting this dual strategy whenever possible, policymakers and decision-makers can gain a more nuanced understanding of the dynamics at play, enabling more effective and context-sensitive policies that balance short-term needs with long-term sustainability. This integrated approach is particularly important for the Blue Economy, where interactions between economic, social, and environmental factors are complex and often time-sensitive.

Additionally, analysing the correlations between different indicators in the Blue Economy context not only helps in making informed decisions but also supports the development of predictive models and hypothesis testing across multiple sectors. This approach serves as a key tool for anticipating future challenges, assessing the potential impacts of policies, and ensuring that development strategies are equitable and inclusive, particularly for marginalised communities in coastal regions. Ultimately, the insights generated by these analytical techniques offer an essential foundation for creating adaptable, sustainable policies that can support the Blue Economy's goals over time. As this field continues to evolve, future research should focus on improving data consistency, expanding longitudinal datasets, and refining analytical methods to address uncertainties and gaps. By continuously refining our approach to the Blue Economy, we can foster more resilient and effective policy frameworks that align with social, economic, and environmental goals, ensuring equitable outcomes across and within countries.

CRediT authorship contribution statement

Pedro C. González-Espinosa: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Gerald G. Singh:** Writing – review & editing, Validation, Methodology. **Andrés M. Cisneros-Montemayor:** Writing – review & editing, Validation, Supervision, Funding acquisition.

Code availability

The code used to perform the analyses can be found in https://doi.org/10.5281/zenodo.13994429.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Pedro C. Gonzalez Espinosa reports financial support was provided by Nippon Foundation Ocean Nexus. Gerald G. Singh reports financial support was provided by Nippon Foundation Ocean Nexus. Andres M. Cisneros Montemayor reports financial support was provided by Nippon Foundation Ocean Nexus. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2025.107589.

Data availability

All datasets were retrieved from publicly available sources. The link to each dataset can be found in the supplementary material.

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